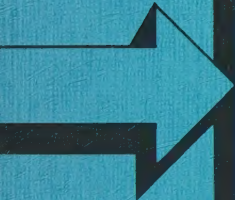


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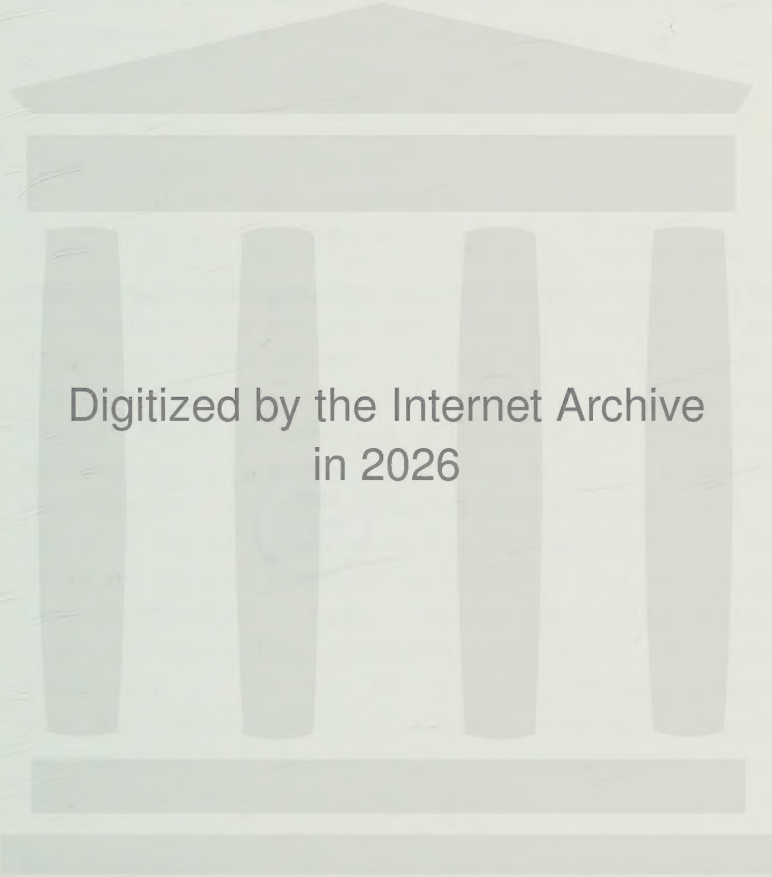
SELF-TUNING REGULATORS

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To Karin,
with thanks for her encouragement and support.



SELF-TUNING REGULATORS.

During the industrial revolution clever engineers heuristically designed regulators which could bring the output of a system back to a reference value after a disturbance. These regulators which are nowadays called PI-regulators (Proportional and Integral regulators) can be described mathematically by the equation

$$u(t) = K \left(e(t) + \frac{1}{T} \int_0^t e(s) ds \right)$$

where u is the control signal and e is the difference between the desired and the actual output of the system. The PI-regulator has the property that the stationary error after a step disturbance is equal to zero irrespective of the system to be controlled if the closed loop system is stable. The first complete analysis of the PI-regulator was done by J.C. Maxwell [5] about 80 years after their construction. Maxwell explained mathematically the importance of the integral term. The PI-regulators are the main tools of control engineering practice. The regulators have been implemented in many different ways using analog technique and mechanical, pneumatic, hydraulic and electronic technology. In the last 10 - 15 years PI-regulators have also been implemented digitally on computers. The ways of implementing the regulators have been different but the basic idea has always been the same.

The PI-regulators are robust and are sufficiently good in many cases. It is also fairly easy to tune the regulator, i.e. to choose its parameters (K and T). The simple PI-regulator is, however, not suitable in all cases and more sophisticated regulators have been developed. More complex regulators are for instance needed if the process contains dead-time. The computer technology has given new pos-

sibilities to implement regulators. Much more complex regulators can be implemented on a computer than if analog technique is used. The growing complexity of the controllers has made the tuning more difficult. The tuning problem is one reason why complex regulator seldom are used.

The tuning problem has two aspects. The parameters of the regulator must be chosen at the start-up. The regulator must also be retuned occasionally if the process dynamics are changing. This has led to the idea of adaptive controllers. The word adaptive implies that the regulator has the ability to change its parameters when the process dynamics or the characteristics of the disturbances are changing. Adaptive controllers have so far not been implemented to any greater extent.

If the parameters of the process are modelled as stochastic processes it is possible to formulate the adaptive control problem within the framework of stochastic optimal control theory. It is, however, difficult to get a practical solution to the problem since the computational requirements are such that only the simplest cases can be solved numerically even with the largest computers available today [1]. The solution has, however, a very interesting structure. Feldbaum [4] has pointed out that these control strategies have a twofold goal. The controller must obtain good estimates of the unknown parameters of the process, i.e. the controller must perform real-time identification. Secondly the controller must make as good control as possible based on the available information. These two goals are contradictory and there must be a compromise between the identification and control activities of the controller. Controllers with these properties are called dual controllers.

One interesting simplification of the adaptive control

problem is obtained if it is assumed that the process to be controlled has constant but unknown parameters. Controllers for this type of processes will be called self-tuning regulators. This thesis treats one type of self-tuning regulators and compromise of the following three parts:

- I. On Self-Tuning Regulators, Automatica, 9, No. 2, March, 1973, pp 185 - 199, Coauthor K.J. Åström,
- II. A Self-Tuning Regulator, Report 7311, Division of Automatic Control, Lund Institute of Technology,
- III. An Industrial Application of a Self-Tuning Regulator, Report 7310, Division of Automatic Control, Lund Institute of Technology, Coauthor U. Borisson.

The thesis covers the steps from analysis to practical implementation of a self-tuning regulator. The regulator is derived to control single-input single-output systems which are minimum phase. One early version was presented by Wieslander and Wittenmark at an IFAC Symposium in Prague 1970 [9]. At the same symposium Peterka presented a similar algorithm [6]. Part I of this thesis was presented at the IFAC World Congress in Paris 1972. Saridis and Dao [8] consider the self-tuning problem when the unknown parameters belong to a known discrete set of parameter values. Åström has in [2] given a self-tuning algorithm which can be used for nonminimum phase systems. A more complex self-tuning regulator which can handle multiple-input multiple-output systems is given by Peterka and Åström [7].

Part I introduces the basic idea behind the considered class of self-tuning regulators based on the natural assumption of separation of identification and control. Some asymptotic results are given. For instance it is shown that if the algorithm converges then the controller under weak assumptions will converge to the minimum variance regulator that can be obtained if the parameters are known.

Part II is a detailed discussion of the properties of the self-tuning regulator. The results are partly obtained through analysis and partly through extensive simulations using an interactive computer program. The simulations have thus been used to gain insight into the properties of the algorithm and to generate hypotheses, some of which were later proved mathematically. The investigation in Part II shall thus be regarded as being theoretical as much as experimental.

Part III relates some of the results obtained from an implementation of a self-tuning regulator on an industrial process.

The self-tuning regulator discussed can be thought of as performing two tasks. The parameters in a model of the process are estimated using the method of least squares and a minimum variance regulator is computed based on the estimated parameters. The steps are repeated in each sampling interval. The computations to be done in each step are very small. It is interesting to compare the complexities of the PI-regulator and the self-tuning regulator. The number of operations (additions or multiplications) in a digital PI-regulator is about 4. The self-tuning regulator with two parameters requires about 34 operations. The number of operations for the self-tuning regulator is increasing with the square of the number of parameters. Experiments and simulations indicate that up to 6 parameters is a reasonable number of parameters in a self-tuning regulator. This means that the information processing is an order of magnitude larger when using a self-tuning regulator. A better performance of the system can, however, compensate for the more complex computations.

It is relatively easy to characterize the asymptotic properties of the self-tuning algorithm. If the parameter estimates converge then

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{t=1}^N y(t+\tau)y(t) = 0$$

and

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{t=1}^N y(t+\tau)u(t) = 0$$

for certain values of τ . This is true for a large class of processes. The self-tuning regulator can thus be compared with a PI-regulator. The PI-regulator will make the control error equal to zero irrespective of the properties of the process as long as the closed loop system is stable. Analogously the self-tuning regulator will make mean values of sums of squares of outputs and inputs equal to zero. The self-tuning regulator will converge to a generalized dead-beat regulator if the changes in the reference signal is dominating and to a minimum variance regulator if the noise is dominating.

The asymptotic properties discussed in Part I are true under the assumption that the parameter estimates really converge. The transient properties of the self-tuning algorithm are difficult to analyze. In Part II the convergence is discussed for some special cases. The algorithm does not converge for all linear single-input single-output systems with constant parameters. This can be shown by counter-examples.

Some parameters must be specified when using the self-tuning regulator. These are a scale factor for the control variables, the number of time-delays in the system, the number of parameters in the regulator, the initial values of the estimates and their covariances. The choice of these parameters is discussed in Part II. Experience has shown that it is fairly easy to make the proper choice

in practice. These parameters are also much easier to choose than to directly determine the coefficients of a complex control law.

The self-tuning regulator presented has been used on different industrial processes. An example from the mining industry is given in [3]. Part III of this thesis gives experiences of one implementation in the paper industry. The process under consideration is moisture content control on a paper machine at the Gruvön mill of Billerud AB, Grums, Sweden. The experiences of the implementation are very good concerning the transient as well as the stationary behaviour of the regulator. The experiments at Gruvön show that it can be easy to implement a self-tuning regulator on a process which already is controlled by a process computer. The engineers at the mill could take over the operation of the self-tuning regulator after a short training period only.

The self-tuning regulator discussed has many attractive properties. It can be used for a large class of linear single-input single-output systems. The algorithm can be used for systems which have slowly time-varying parameters. It has turned out that even nonminimum phase systems can sometimes be handled. Finally the algorithm is easy to implement on a computer and to install on a real process. Among the drawbacks are the fact that the algorithm does not always converge. Further it is not possible to automatically handle nonminimum phase systems which is possible with the algorithm described in [2]. The presented algorithm can only handle single-input single-output systems. Multivariable systems can, however, be handled through cascade control. It is also believed that the results can be extended to certain multivariable systems.

It is the belief of the author of this thesis that the

presented self-tuning regulator is a valuable tool for control engineers. It should be pointed out that the self-tuning regulator is not a substitute for but a good complement to the conventional PI-regulators.

The thesis has been possible to accomplish thanks to many persons in my environment. First of all I want to express my sincere thanks to my advisor Karl Johan Åström whose ideas, help and enthusiasm have guided and encouraged me throughout the work.

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